Large Field Inflations from Higher-Dimensional Gauge Theories

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Introduction and motivation

- Recent detection of B-mode polarization of CMB by BICEP2.

- If the B-mode polarization is primordial origin the large tensor to scalar ratio $r \simeq 0.16$ implies trans-Planckian field excursion $\Delta\phi > M_P$ during inflation via the Lyth bound and require the knowledge of physics near Planck scale.

- It is not easy to protect the flatness of the inflaton potential from the quantum corrections over trans-Planckian field range in effective field theory (EFT) framework.

- Gauge symmetry in higher-dim. gives rise to the approximate shift symmetry in 4D scalar potential and this mechanism was applied to inflation - extranatural inflation $\phi \sim A_5^{(0)}$

[Arkani-Hamed et al, 03]

$$V(\phi) \sim \frac{1}{L^4} \sum_n^{\infty} \frac{1}{n^5} \cos\left(n \frac{\phi}{f}\right) \qquad f = \frac{1}{g(2\pi L)} \text{ : decay constant}$$

consequence of the model, $f > M_P$ ➡ large field

validity of the EFT ⇒ $L^{-1} < M_P$ ➡ $g \sim 10^{-5}$

- The inflaton potential is generated through loop corrections and flatness and smallness of the potential is protected by the naturalness in the sense of 't Hooft. ['tHooft,79]

- Although extranatural inflation is a good realization of large field inflation, it is difficult to embed it to UV completion theory (String theory) due to tiny gauge coupling: it may cause an obstacle for coupling EFT to gravity

  \- Weak gravity conjecture $\Lambda_{UV} \lesssim \sqrt{2} g M_P$

  [Arkani-Hamed et al, 06]

- We study large field inflation models from higher-dim. gauge theories.

- Important theoretical ingredients in our EFT approach are
  - naturalness of gauge theory parameters
  - weak gravity conjecture(WGC) ➡ $2\pi f \lesssim M_P\,, \qquad f = 1/(2\pi g L)$

- The models we study are type in which the defining theory are sub-Planckian but inflation effectively travels trans-Planckian field range. Good inflaton potentials have already been proposed.

  - Single axion monodromy
  - Dante's Inferno
  - Axion alignment,
  - Axion hierarchy

- Originally the axion models for inflaton potential is designed for deriving from string theory.

- Our model construction is a bottom-up approach and we try to investigate the axion type potentials from the higher-dim. gauge theory point of view.

- It is easy to “derive” the known good potentials in our EFT framework by using concrete theories.

Single Axion monodromy

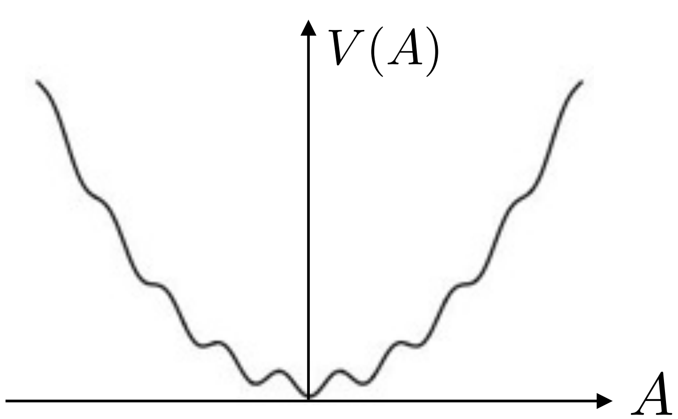
[Silverstein et al, 08]

$$V(A) = \frac{1}{2}m^2A^2 + \Lambda^4\left(1 - \cos\left(\frac{A}{f}\right)\right)$$

- Due to the quadratic term, the potential energy does not return the same under the shift $A \to A + 2\pi f$
- This model effectively reduces to chaotic model $V \sim \frac{1}{2}m^2A^2$ when the slope of the sinusoidal potential is much smaller than that of the mass term during inflation.

$$\Lambda^4/f \ll m^2 A_* \quad * : \text{at horizon exit}$$

- Even if the fundamental field has sub-Planckian period $2\pi f$, the trans-Planckian excursion can be effectively achieved by going round circle several times.



The potential can be derived from a 5D $U(1)$ gauge theory

$$S=\int d^5x\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\frac{1}{2}m^2\left(A_\mu-g_5\partial_\mu\theta\right)^2+(\text{matters})\right]\qquad(\mu=0,\cdots,3,5)$$

- The inflaton field A comes from the zero mode of A_5 after S^1 compactification.

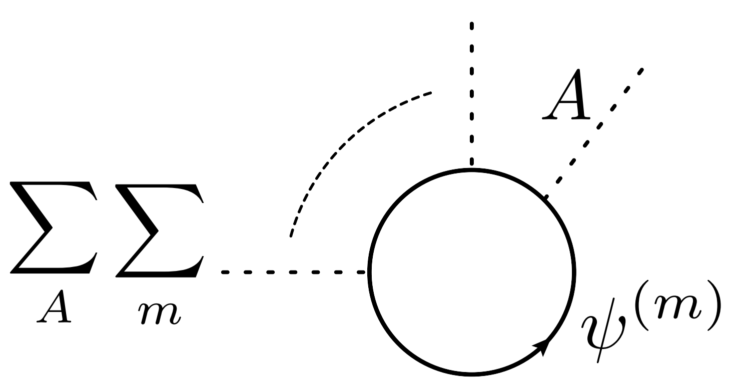
$$A=\sqrt{2\pi L}A_5^{(0)}\qquad L: S^1 \text{ radius}$$

- We introduced the Stueckelberg mass term which gives rise to the quadratic term in the effective potential.

- The one-loop effective potential of $A_5^{(0)}$ is obtained as

$$V(A_5^{(0)})_{1-\text{loop}}=\frac{m^2}{2}A_5^{(0)2}+\frac{3}{\pi^2(2\pi L)^4}\sum_{n=1}^{\infty}\frac{1}{n^5}\cos\left(nA_5^{(0)}(2\pi gL)\right)+\text{const.}$$

$$g=\frac{g_5}{\sqrt{2\pi L}}\ \text{: 4d gauge coupling}$$



$n=1$ is a good approximation.

- At one-loop, the Stueckelberg mass is not renormalized.

- The parameters in the axion monodromy model are related to the parameters in the 5D gauge theory as

$$f = \frac{1}{g(2\pi L)}, \quad \Lambda^4 = \frac{c}{\pi^2 (2\pi L)^4}, \quad c \sim \mathcal{O}(1)$$

$\Lambda^4/f \ll m^2 A_*$, $g \sim \mathcal{O}(1)$ and CMB data with $r = 0.16$ require

$$1.0 \times 10^{14}\,\mathrm{GeV} < \frac{1}{L} < 3.2 \times 10^{16}\,\mathrm{GeV}, \quad m^2 \sim 10^{26}\mathrm{GeV} \ll H_*^2 \quad (H_* \simeq 10^{14}\mathrm{GeV})$$

$\Delta A > M_P$: trans-Planckian field excursion

- The small m^2 is natural in the sense of 't Hooft if the shift symmetry $A \to A + C$ is a good symmetry at the Planck scale. But it is beyond the scope of higher-dim. gauge theory so we can not ensure the naturalness of small $m < H$.

Dante's Inferno(DI)

an improvement of single axion: all fundamental quantities are sub-Planckian

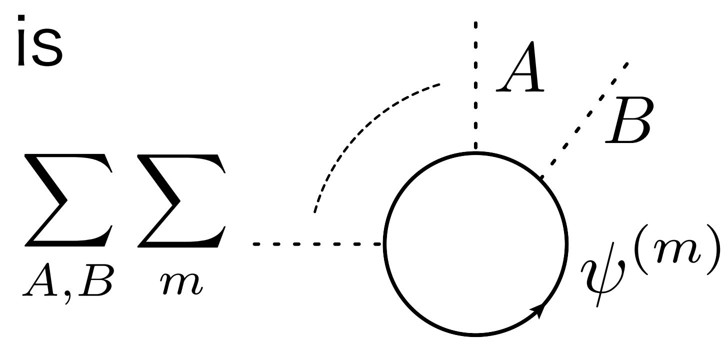
[Berg et al, 08]

$$V(A,B) = \frac{1}{2}m_A^2 A^2 + \Lambda^4\left(1-\cos\left(\frac{A}{f_A}-\frac{B}{f_B}\right)\right)$$

- This type of potential is derived from a 5D gauge theory

$$S = \int d^5x\Big[-\frac{1}{4}F^A_{\mu\nu}F^{A\mu\nu} - \frac{1}{2}m_A^2\left(A_\mu - g_{A5}\partial_\mu\theta\right)^2 - \frac{1}{4}F^B_{\mu\nu}F^{B\mu\nu}$$
$$- i\bar{\psi}\gamma^\mu\left(\partial_\mu + ig_{A5}A_\mu - ig_{B5}B_\mu\right)\psi\Big]$$

with a matter which has two kinds of charges belongs to $U_A(1)$ and $U_B(1)$ and corresponding one-loop diagram is



Two inflaton fields are defined by

$$A,\ B = \sqrt{2\pi L}A_{5(0)},\ \sqrt{2\pi L}B_{5(0)}$$

- The parameters of DI are written in terms of the parameters of the 5D theory as

$$\Lambda^4 \simeq \frac{3}{\pi^2}\frac{1}{(2\pi L)^4} \qquad f_{A,B} = \frac{1}{g_{A,B}(2\pi L)} \qquad g_{A,B} = \frac{g_{A5,B5}}{\sqrt{2\pi L}}$$

It is convenient to rotate the fields as

$$\begin{pmatrix} \tilde{B} \\ \tilde{A} \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} B \\ A \end{pmatrix}, \qquad \sin\xi = \frac{f_A}{\sqrt{f_A^2 + f_B^2}}, \quad \cos\xi = \frac{f_B}{\sqrt{f_A^2 + f_B^2}}.$$

Then the potential takes the form,

$$V(\tilde{A}, \tilde{B}) = \frac{m_A^2}{2}\left(\tilde{A}\cos\xi + \tilde{B}\sin\xi\right)^2 + \Lambda^4\left(1 - \cos\frac{\tilde{A}}{f}\right), \qquad f \equiv \frac{f_A f_B}{\sqrt{f_A^2 + f_B^2}}$$

In this model, the regime of interest is consistent with WGC

$$2\pi f_A \ll 2\pi f_B \lesssim M_P \qquad \cos\xi \simeq 1, \quad \sin\xi \simeq \frac{f_A}{f_B}, \quad f \simeq f_A$$

Model constraints for DI:

$$\frac{\Lambda^4}{f} \gg m_A^2 A_{in}, \quad \frac{\partial^2}{\partial \tilde{A}^2} V(\tilde{A}, \tilde{B}) > H^2$$

⇒ $\tilde{A}$ is heavy and can be integrated out, then inflation occurs along with a bottom of the sinusoidal potential

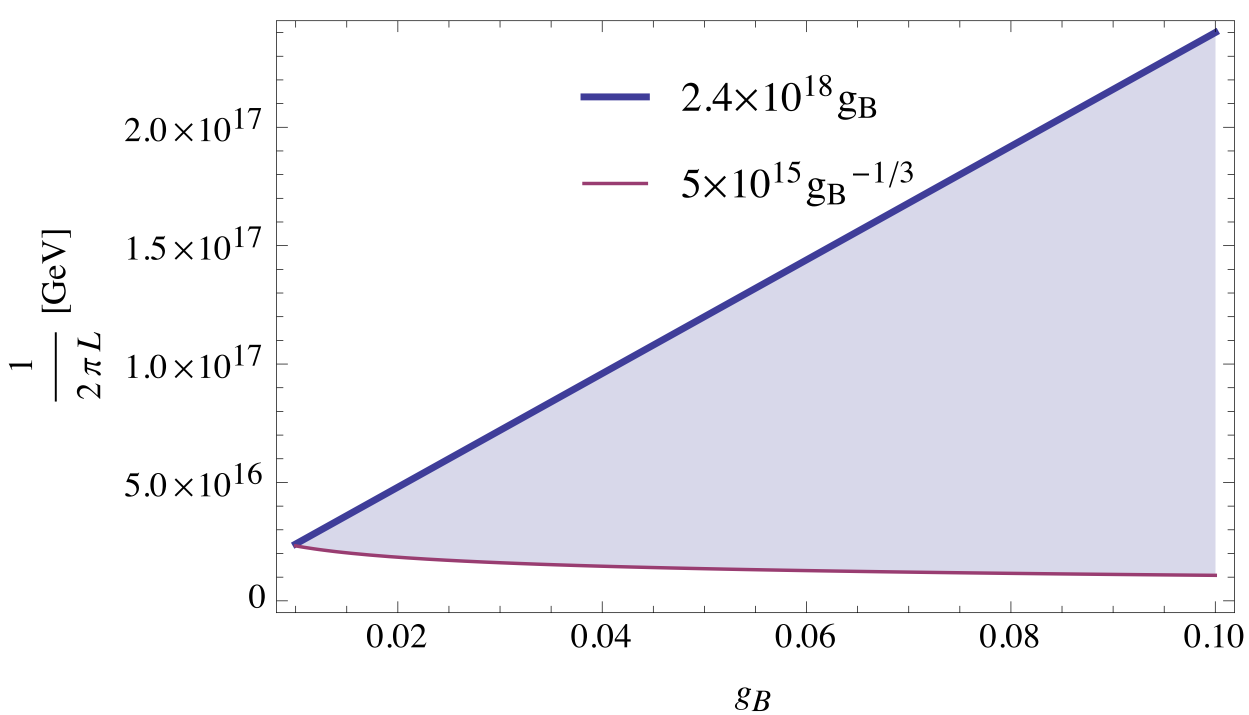
DI model is effectively reduced to chaotic model, identifying $\tilde{B}$ with inflaton, $\phi \equiv \tilde{B}$.

$$V_{\rm eff}(\phi) = \frac{m^2}{2}\phi^2, \qquad m \equiv \frac{f_A}{f_B} m_A\,, \qquad\qquad A \sim \frac{f_B}{f_A}\phi$$

$\Delta\phi \simeq 13 M_P$ and $m \simeq 10^{13}\mathrm{GeV}$ can be realized thanks to the factor f_A/f_B even if $\Delta A, \Delta B < M_P$, and the original mass $m_A \gtrsim H$.

The constraints for Dante's Inferno is written in terms of the parameters of the 5D gauge theory as

$$g_A > 14 g_B, \qquad g_B^{-1/3} \times 3.2 \times 10^{16}\,\mathrm{GeV} < \frac{1}{L} \lesssim g_B \times 2.4 \times 10^{18}\,\mathrm{GeV}$$



The allowed values of the gauge couplings and the compactification radius are rather restricted.

Axion Alignment & Axion Hierarchy:
improvement of natural inflation

[Kim et al, 08, Ben-Dayan et al. 14]

Both models can be described by the potential of the form

$$V(A,B) = \Lambda_1^4\left(1-\cos\left(\frac{m_1}{f_A}A+\frac{n_1}{f_B}B\right)\right)+\Lambda_2^4\left(1-\cos\left(\frac{m_2}{f_A}A+\frac{n_2}{f_B}B\right)\right)$$

The main feature of these two models is to acquire a large effective decay const. $f_{\rm eff} > M_P$ from the (small) scales f_A and f_B by defining the eigenvectors of the mass matrix. $\Delta A, \Delta B < M_P$ is satisfied.

$$\begin{pmatrix}\phi_s\\ \phi_l\end{pmatrix} = \begin{pmatrix}\cos\zeta & \sin\zeta\\ -\sin\zeta & \cos\zeta\end{pmatrix}\begin{pmatrix}A\\ B\end{pmatrix}$$

where

$$\cos\zeta = \frac{f_s}{f_A}m_1, \quad \sin\zeta = \frac{f_s}{f_B}n_1, \qquad f_s = \frac{1}{\sqrt{\frac{m_1^2}{f_A^2}+\frac{n_1^2}{f_B^2}}}$$

In terms of two physical fields

$$V(\phi_s, \phi_l) = \Lambda_1^4 \left(1 - \cos\left(\frac{\phi_s}{f_s}\right)\right) + \Lambda_2^4 \left(1 - \cos\left(\frac{\phi_s}{f_s'} + \frac{\phi_l}{f_l}\right)\right),$$

effective decay constant: $f_l = \dfrac{\sqrt{m_1^2 f_B^2 + n_1^2 f_A^2}}{m_1 n_2 - m_2 n_1}$

Axion alignment model

$$|m_1 n_2 - m_2 n_1| \ll |m_1|, |n_1| \;\Rightarrow\; |f_l| \gg f_A, f_B \;\; (f_s, f_s')$$

ϕ_s : heavy, $m_{\phi_s} > H$, irrelevant to inflation

ϕ_l : light, $m_{\phi_l} < H$, identified with the inflaton

Axion hierarchy model $(n_2 = 0)$

$$\left|\frac{f_A}{m_1}\right| \ll \frac{f_A}{|m_2|}, \frac{f_B}{|n_1|} \quad \Rightarrow \quad |f_l| \simeq \left|\frac{m_1}{n_1 m_2}\right| f_B$$

The two models reduce to natural inflation with the effective constants.

The potential is derived from the 5D action with two kinds of matters.

$$S = \int d^5x \Big[-\frac{1}{4}F^A_{\mu\nu}F^{A\mu\nu} - \frac{1}{4}F^B_{\mu\nu}F^{B\mu\nu}$$
$$- i\bar{\psi}\gamma^\mu(\partial_\mu + ig_{A5}m_1A_\mu + ig_{B5}n_1B_\mu)\psi - i\bar{\chi}\gamma^\mu(\partial_\mu + ig_{A5}m_2A_\mu - ig_{B5}n_2B_\mu)\chi \Big]$$

Assumption: m_1, m_2, n_1, n_2 are all integers

WGC and Natural inflation + $r = 0.16$ require $2\pi f_B \lesssim M_P$ and $|f_l| \gtrsim 20M_P$

Axion alignment

$$|m_1n_2 - m_2n_1| \ll |m_1|, |n_1|$$

➡ $\max(|m_1|, |n_1|) \gtrsim 20 \times 2\pi$, a matter with large charge $\sim \mathcal{O}(100)$

or fine-tuning, $|m_1n_2 - m_2n_1| \ll 1$

Axion hierarchy

$$|f_l| \simeq \left|\frac{m_1}{n_1m_2}\right| f_B \quad \Rightarrow \quad |m_1| \gtrsim 20|n_1m_2| \times 2\pi$$

a large hierarchy between the charges in the same gauge group $U_A(1)$

Summary

- Various axion inflation models can be derived from the higher-dimensional (5D) gauge theories.

- The allowed range of the gauge theory parameters are quite constrained.

- Among the model studied, Dante's Inferno model appears as the most natural model in this framework,

- Single field axion monodromy leaves the problem that whether the shift sym. is a good sym. or not to its UV.

Back up slide: Weak gravity conjecture

[Arkani-Hamed et al, 06]

- WGC assert the existence of a state with charge q and mass satisfying $$\frac{gq}{\sqrt{4\pi}} \geq \sqrt{G_N} m = \frac{m}{\sqrt{8\pi} M_P}$$ $g: U(1)$ coupling
- Extremal black holes can loose their charge by emitting such particles.
- Monopole with unit magnetic charge $$q_m = \frac{4\pi}{g}, \quad m_m \simeq \frac{4\pi \Lambda_{UV}}{g^2}$$

WGC reads $$\Lambda_{UV} \lesssim \sqrt{2} g M_P$$

Usage of higher-dim. gauge theory is justified if $L^{-1} < \Lambda_{UV}$

$\Rightarrow$ $$2\pi f \lesssim M_P\,, \qquad f = 1/(2\pi g L)$$

(It is by chance almost the same as the constraint on axion models from string theory)